NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3457

ESTIMATION OF INLET LIP FORCES AT SUBSONIC AND SUPERSONIC SPEEDS

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SUMMARY

The effects of inlet lip thickness on inlet performance are estimated as functions of mass flow for subsonic and supersonic flight speeds. At subsonic speeds, pressure-recovery losses and additive drag are shown to decrease linearly with increasing lip frontal area if the maximum suction force is realized. At supersonic speeds, inlet drag increases linearly with inlet lip frontal area at full mass flow. For reduced mass flow, some reduction in total drag is possible with lips of moderate thickness, but the magnitude of this reduction decreases as flight speed increases.

INTRODUCTION

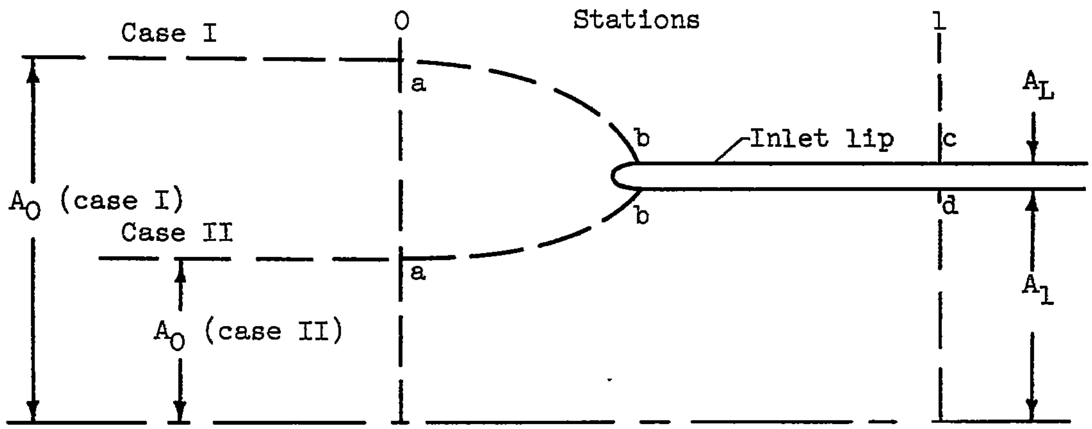
Pressure-recovery losses and drag due to the use of sharp inlet lips at subsonic speeds are evaluated in reference 1. These losses arise because the expected suction force (as calculated, e.g., in ref. 2) is not physically possible when the lips are sharp.

At supersonic speeds, a suction force arises on blunt lips when the inlet flow is reduced in a manner that produces a detached shock wave ahead of the inlet. The variation of this suction force with lip thickness is estimated in reference 2.

The purpose of this note, prepared at the NACA Lewis laboratory, is to present a unified one-dimensional treatment of subsonic and supersonic lip forces and to eliminate certain gaps in published analyses, so that the advantages and disadvantages of using blunt lips can be evaluated easily.

ANALYSIS

The analysis is based on the momentum theorem as applied to the idealized lip configuration shown in sketch (a):



Sketch (a)

Equations are derived in terms of area ratios, so that results are applicable to all types of cylindrical shell, including the two-dimensional. (Symbols used are defined in the appendix.) Case I, which applies only for subsonic flow, illustrates the relation between the inlet lip dbc and the stagnation streamline abc when the mass-flow ratio (defined as the ratio of capture area to inlet area, A_0/A_1) is greater than unity. Case II, which applies for both subsonic and supersonic flow (with a detached shock wave in the latter case), represents the stagnation streamline for mass-flow ratios A_0/A_1 less than unity. In case I, the external flow is isentropic for all lip thicknesses, but the internal flow may, for sufficiently thin lips, sustain total-pressure loss due to separation as the air passes around the 180° turn. In case II, with subsonic flow, the internal flow is isentropic, but the external flow may sustain separation losses which produce a net drag.

The pressure-drag coefficient of the lip $C_{D,L}$ is for all cases the difference between the integrated pressure coefficient along the external streamline abc and that along the internal streamline abd. Thus,

$$C_{D,L} \equiv \int_{dbc} C_p \frac{dA_p}{A_1} = \int_{abc} C_p \frac{dA_p}{A_1} - \int_{abd} C_p \frac{dA_p}{A_1} \equiv C_{D,e} - C_{D,i} \qquad (1)$$

where A_p is projected area normal to the free-stream direction.

The portion of the drag integrals from a to b is usually called the "additive drag." If the additive drag plus the external lip drag

$C_{D,e}$ is less than the additive drag plus the internal lip drag $C_{D,i}$, a lip suction force is indicated by equation (1). This suction force is not physically realizable, however, if it is greater than the force corresponding to a vacuum over the entire projected area of the lip A_L. Consequently, the maximum suction-force coefficient is, as pointed out in reference 2,

$$C_{D,L,max} = -\frac{2}{\gamma M_0^2}\frac{A_L}{A_1} \tag{2}$$

corresponding to zero pressure over the entire lip. If a fraction K of this maximum suction force is actually realized, the lip-force coefficient can be written

$$C_{D,L} = -\frac{2K}{\gamma M_0^2}\frac{A_L}{A_1} \tag{3}$$

Equation (3) specifies the lip suction coefficient for all cases when the lip area A_L is less than some critical value denoted by $A_{L,cr}$. For lip areas larger than $A_{L,cr}$, full suction force is physically attainable, and $C_{D,e}$ and $C_{D,i}$ can be evaluated analytically from the momentum and pressure at station 1 (sketch (a)). The critical value of A_L is therefore obtained by setting the suction force of equation (3) equal to that of equation (1):

$$\frac{A_{L,cr}}{A_1} = -\frac{\gamma M_0^2}{2K}\left(C_{D,e} - C_{D,i}\right) \tag{4}$$

For A_L less than $A_{L,cr}$, either $C_{D,i}$ or $C_{D,e}$ must be found in terms of the suction force given by equation (3). When these drag coefficients are known, the inlet pressure loss and total drag can be found as functions of inlet lip area.

Case I: Subsonic Flow with $A_0 > A_1$

For case I, $C_{D,e} = 0$, since net external drag for subsonic potential flow is zero. The internal drag $C_{D,i}$ is, by the momentum theorem,

$$C_{D,i} = \frac{\frac{p_1}{p_0} - 1}{\frac{\gamma}{2} M_0^2} - 2\frac{A_0}{A_1}\left(1 - \frac{u_1}{u_0}\right) \tag{5}$$

which is, by equation (1), equal to the negative of the suction-force coefficient. Since total-pressure losses are incurred in this case only if $A_L < A_{L,cr}$, the suction force of interest is given by equation (3). The total-pressure loss corresponding to leading-edge areas in this range is obtained from equations (1), (3), and (5), using well-known Mach number functions for u_1/u_0 and p_1/p_0 and solving for P_1/P_0. The result is

$$\frac{P_1}{P_0} = \frac{1 + K\left(\frac{A_L}{A_1}\right)}{\frac{\left(\frac{p}{P}\right)_1}{\left(\frac{p}{P}\right)_0}\left[1 + \gamma M_1^2 - \gamma M_0^2 \frac{\left(M \frac{a_a}{a}\right)_1}{\left(M \frac{a_a}{a}\right)_0}\right]} = \left(\frac{P_1}{P_0}\right)_{A_L=0}\left(1 + \frac{KA_L}{A_1}\right) \tag{6}$$

where $(P_1/P_0)_{A_L=0}$ is the value obtained in reference 1 for zero-thickness lips.

The ratio of actual to maximum possible mass flow is

$$\frac{m}{m_{max}} = \frac{P_1}{P_0}\left(\frac{A^*}{A}\right)_{M_1} \tag{7}$$

where m_{max} is the maximum mass flow with $P_1 = P_0$ and choked inlet. The critical value of A_L/A_1 for which P_1/P_0 reaches unity is, from equation (6),

$$\frac{A_{L,cr}}{A_1} = \frac{1}{K}\left[\left(\frac{P_1}{P_0}\right)_{A_L=0}^{-1} - 1\right] \tag{8}$$

For values of A_L/A_1 less than critical, and for constant K, both P_1/P_0 and m/m_{max} decrease linearly as lip frontal area decreases.

Case II: Subsonic Flow with $A_0 < A_1$

For case II with subsonic flow, the internal flow is isentropic. Of interest, therefore, is the total external drag $C_{D,e}$ produced because

3721

suction force is not fully realized for $A_L < A_{L,cr}$. From equations (1), (3), and (5),

$$C_{D,e} = C_{D,i} + C_{D,L} \equiv \frac{\frac{p_1}{p_0} - 1}{\frac{\gamma}{2} M_0^2} - 2 \frac{A_0}{A_1}\left(1 - \frac{u_1}{u_0}\right) - \frac{2K}{\gamma M_0^2} \frac{A_L}{A_1} \tag{9}$$

3721 Using isentropic flow relations for p_1/p_0, u_1/u_0, and A_0/A_1 yields

$$C_{D,e} = \frac{2}{\gamma M_0^2}\left[\frac{\left(\frac{P}{p}\right)_0}{\left(\frac{P}{p}\right)_1}\left(1 + \gamma M_1^2\right) - 1\right] - 2 \frac{\left(\frac{P}{p}\right)_0}{\left(\frac{P}{p}\right)_1} \frac{\left(M \frac{a_a}{a}\right)_1}{\left(M \frac{a_a}{a}\right)_0} - \frac{2K}{\gamma M_0^2} \frac{A_L}{A_1}$$

$$\equiv \left(C_{D,e}\right)_{A_L=0} - \frac{2K}{\gamma M_0^2} \frac{A_L}{A_1} \tag{10}$$

where $\left(C_{D,e}\right)_{A_L=0}$ is the external drag coefficient obtained in reference 1 for sharp-lip inlets. The critical inlet lip area is that for which $C_{D,e} = 0$; that is,

$$\frac{A_{L,cr}}{A_1} = \frac{\gamma M_0^2}{2K} \left(C_{D,e}\right)_{A_L=0} \tag{11}$$

For lip areas less than critical (again for constant K), the net external drag coefficient $C_{D,e}$ increases linearly as A_L decreases.

Case II: Supersonic Flow

For case II with supersonic flow, a reduction in mass flow by means of an exit flow control produces a detached shock wave ahead of the inlet lip. As pointed out in reference 3, the drag associated with this type of spillage is equal to the drag of a blunt body having the shape of the stagnation streamline. Consequently, the external drag (additive plus lip) can be approximated by

$$C_{D,e} = C_{D,b}\left(\frac{A_1 - A_0 + A_L}{A_1}\right) = C_{D,add}\ (\text{ref. } 3) + C_{D,b} \frac{A_L}{A_1} \tag{12}$$

where $C_{D,b}$ is the drag coefficient of a two-dimensional blunt body and is, by the method of reference 3, a function only of Mach number. The quantity $C_{D,add}$ (ref. 3) is the additive drag coefficient evaluated in reference 3 for sharp-lip inlets.

The internal drag coefficient $C_{D,i}$ is given by equation (5) and is identical to the additive drag computed by the internal momentum method of reference 4. The lip-force coefficient with A_L large enough for full suction is, therefore,

$$C_{D,L} = C_{D,add}\ (\text{ref. } 3) - C_{D,add}\ (\text{ref. } 4) + C_{D,b}\frac{A_L}{A_1} \tag{13}$$

This equation differs from that of reference 2 only in the use of the detached-shock-wave theory of reference 3 in place of the normal-shock method.

For $A_L < A_{L,cr}$, the suction-force coefficient is again

$$C_{D,L} = -\frac{2K}{\gamma M_0^2}\frac{A_L}{A_1}$$

The critical lip area is therefore given by

$$\frac{A_{L,cr}}{A_1} = \frac{C_{D,add}\ (\text{ref. } 4) - C_{D,add}\ (\text{ref. } 3)}{C_{D,b} + \dfrac{2K}{\gamma M_0^2}} \tag{14}$$

The total external drag coefficient for $A_L < A_{L,cr}$ is

$$C_{D,e} = C_{D,add}\ (\text{ref. } 4) - \frac{2K}{\gamma M_0^2}\frac{A_L}{A_1} \tag{15}$$

while, for $A_L > A_{L,cr}$, equation (12) applies.

DISCUSSION OF RESULTS

The critical lip-area ratio $A_{L,cr}/A_1$ is shown in figure 1 for cases I, II (subsonic), and II (supersonic). Curves are shown for $K = 1.0$ and (in a few cases) for $K = 0.9$. With these curves, the reduction in subsonic losses due to use of blunt instead of sharp inlet

3721

lips can be estimated. For a fixed value of K, pressure-recovery loss or drag decreases linearly with A_L/A_1 from the sharp-lip values of reference 1 to zero at the critical lip-area ratio.

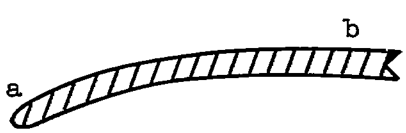
The penalties at supersonic speeds corresponding to the gains resulting from the use of blunt lips at subsonic speeds can be determined from figure 2, where the external inlet drag coefficient is plotted against lip-area ratio for several Mach numbers and mass-flow ratios. These curves again apply for $K = 1.0$, except for the few curves for which $K = 0.9$ was used. Comparison of the reduced mass-flow curves shows that the possible reduction in drag becomes negligibly small at Mach numbers above 2.0, even for very low mass flow. As an example of the penalties at supersonic speeds due to the use of blunt lips, suppose it is desired to increase the inlet total-pressure recovery at zero forward speed and maximum mass flow from the sharp-lip value of 0.79 (ref. 1) to 0.85. For $K = 1.0$, the inlet lip area required is, by linear interpolation,

$$\frac{A_L}{A_1} = \frac{0.85 - 0.79}{1.0 - 0.79}\left(\frac{A_L}{A_1}\right)_{cr} = \left(\frac{0.06}{0.21}\right)(0.265) = 0.076$$

From figure 2 the net external drag at full mass flow is then 0.035 at $M_0 = 1.2$ and 0.085 at $M_0 = 2.0$. For a mass-flow ratio of 0.7, the net external drag is reduced from the sharp-lip value of 0.265 to 0.19 at $M_0 = 1.2$ and is increased from 0.42 to 0.44 at $M_0 = 2.0$.

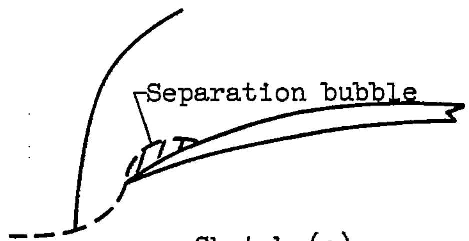
CONCLUDING REMARKS

Results of this analysis are, of course, subject to the usual limitations of one-dimensional analyses. Thus, the suction force is independent of lip shape in the analysis, although some difference in force would be expected between (for example) a flat-face lip and a circular lip. Furthermore, cowlings such as that illustrated in sketch (b), which are more common than the idealized version used in sketch (a), cannot be treated by one-dimensional analysis, although an estimate of the net drag could be made by adding the pressure drag along ab to the value computed for the straight shell of sketch (a). Another case that cannot be evaluated by these methods is illustrated in sketch (c), wherein separation on a curved lip can produce a suction force even though the lip itself is sharp. It is possible that the separation bubble on an inclined lip effectively rounds the leading edge sufficiently so that



Sketch (b)

much of the full suction force is realized. If this is true, then it is more accurate to use equation (12) rather than equation (15) for this case, since equation (12) includes all drag components (including full suction force) up to the sonic point, whereas equation (15), with $A_L = 0$, contains no suction force. Again, the pressure drag along the curved contours beyond the separation bubble must be added to estimate the total drag due to flow spillage and lip forces.



Sketch (c)

The preceding discussion illustrates the limitations of the one-dimensional analysis when realistic lip shapes are considered. Despite these limitations, however, the analysis is adequate to formulate certain conclusions regarding the desirability of using rounded rather than sharp lips. The assumption that vacuum, or nearly vacuum, exists over the entire lip for $A_L < A_{L,cr}$ yields the maximum possible benefits that can be derived from blunting the lips. If this benefit is not sufficient to warrent the drag loss suffered with full mass flow at supersonic speeds, then no further refinements are needed. If more accurate lip-force estimates are desired, they must at present be determined experimentally, since there is as yet no way of predicting the magnitude of the suction factor, K as function of Mach number, lip shape, and frontal area.

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3721

APPENDIX - SYMBOLS

The following symbols are used in this report:

A	area
$(A^*/A)_M$	isentropic area contraction ratio from Mach number M to sonic speed
a	speed of sound
a_a	stagnation speed of sound
C_D	drag coefficient
C_p	pressure coefficient
K	ratio of actual suction force to suction force corresponding to full vacuum
M	Mach number
m	mass flow
P	total pressure
p	static pressure
u	velocity
γ	ratio of specific heats

Subscripts:

add	additive
b	blunt body
cr	critical
e	external
i	internal
L	lip
max	maximum

p projected normal to free-stream direction

0 free-stream

1 inlet

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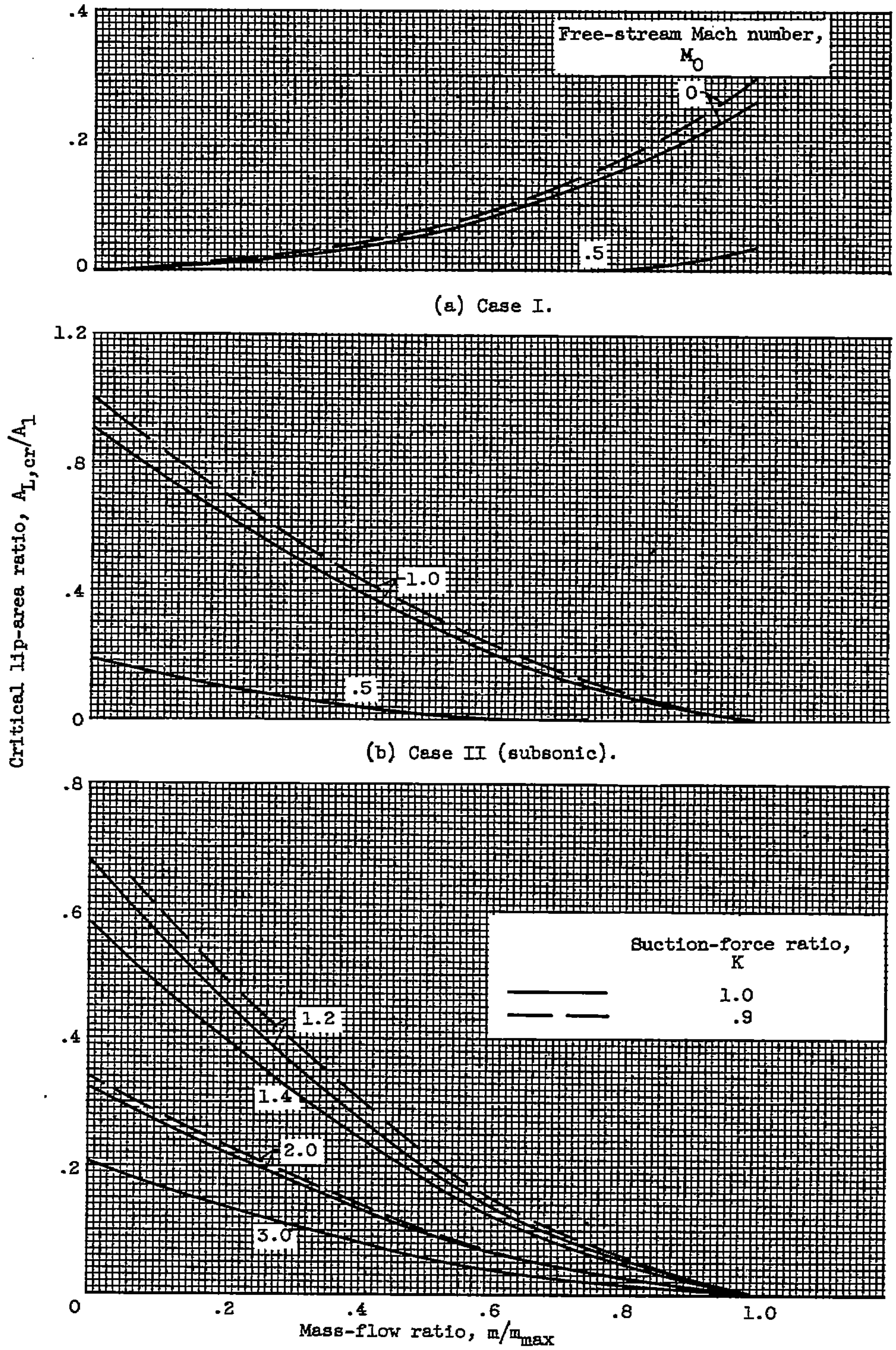

(a) Case I.

(b) Case II (subsonic).

(c) Case II (supersonic).

Figure 1. - Lip frontal area required to attain full theoretical suction force.

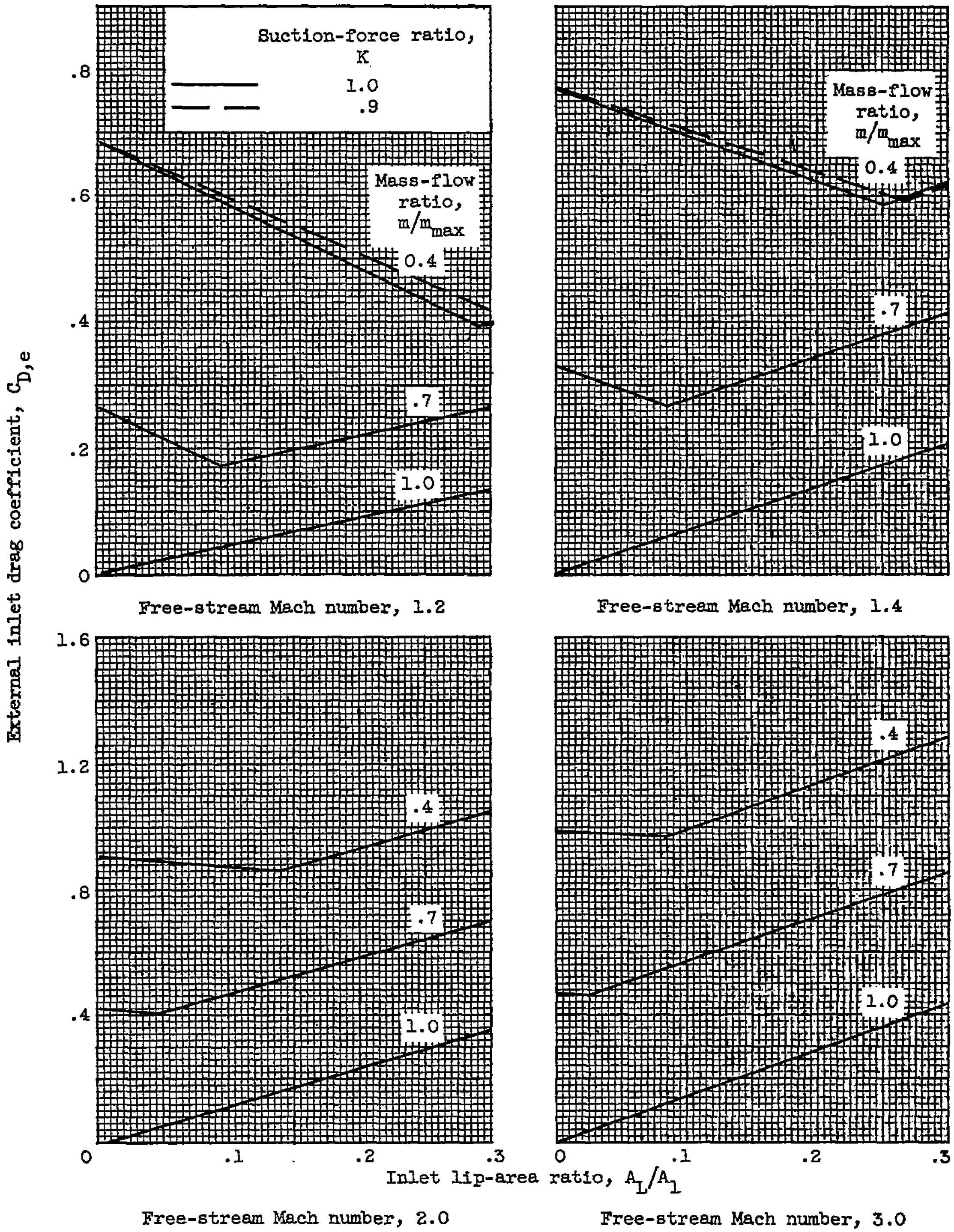

Figure 2. - Combined additive drag and lip-force coefficients.